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Final Technical Report

for

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NASA - Ames Research Center

Numerical Study of Internal Flows and Boundary-Layer Control in Inlets of Turbojet Engines

Submitted by

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Abstract

The performance and efficiency of any turbojet engine and the aircraft propelled by that engine depend strongly upon the engine's inlet. The importance of inlets and their proper design has lead numerous investigators to use numerical methods to study details of the flow field both inside and outside of inlets. Though much progress has been made in the numerical study of flows through inlets, additional research is still needed in the areas of turbulence modelling for transonic flows and boundary layer control via bleed holes. Under NASA grant NAG 2-709, which started on 1 January 1991 and ended on 31 December 1993, research was conducted to address this issue. This final report outlines the achievements made under this grant, which were accomplished in close collaboration with Dr. W. J. Chyu of NASA - Ames Research Center.

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I. Introduction

The performance and efficiency of any turbojet engine and the aircraft propelled by that engine depend strongly upon the engine's inlet. This is because the inlet determines the amount of air entering the engine, velocity and pressure of the air at the face of the engine's compressor, and how presence of the engine affects the high-lift/low-drag aerodynamics of the aircraft [e.g., see Reference 1].

The importance of inlets and their proper design has lead numerous investigators to use numerical methods to study the details of the flow field both inside and outside of inlets [see References 1-4 and the reference listed there]. Though much progress has been made in the numerical study of flows through inlets, additional research is still needed in the areas of turbulence modelling for transonic flows and boundary layer control via bleed holes.

Under NASA grant NAG 2-709, which started on 1 January 1991 and ended on 31 December 1993, research was conducted to address these two issues with attention focused on the following objectives:

1. Modify the F3D/OVERFLOW code developed at NASA - Ames Research Center so that it can be used with differential-equation turbulence models such as the k-ε model.
2. Develop and evaluate turbulence models for transonic flows that take place within inlets.
3. Study numerically the details of the transonic flow field about bleed holes and boundary layer control via bleed holes.

The purpose of this final report is to describe the accomplishments made during each of the three years under the grant in relation to the objectives stated above. At this point, it is emphasized that the accomplishments were made in close collaboration with Dr. W.J. Chyu of NASA - Ames Research Center.

II. Description of Accomplishments

The accomplishments made under each of the three years of the grant under NAG 2-709 are described below.

2.1 FIRST YEAR

During the first grant year beginning on January 1, 1991 and ending on December 31, 1991, the following accomplishments were made:

1. Completed a two-dimensional numerical study on how the following parameters influence the effectiveness of bleed holes in controlling shock-wave induced flow separation on a flat plate with one or two bleed holes that vent to a plenum:
    a. The location of the bleed hole in relation to where the shock wave impinges on the boundary layer.
    b. The size of the bleed hole in relation to the boundary layer thickness.
    c. The number of bleed holes and the spacing between them.
    d. The ratio of bleed hole width to its depth.

    This study showed the details of the flowfield about bleed holes as a function of the aforementioned parameters and revealed how the plenum affects the bleed process. This work is described in Ref. 5.
2. RAAKE, a code developed by the principal investigator of this proposal and Dr. Chyu for computing turbulent compressible flows, was made much more robust. This robustness was achieved by treating viscous terms implicitly in conjunction with the LU algorithm. This work is described in Ref. 6.
3. RAAKE was tested on the following test problem with experimental data: subsonic boundary layer flow past a flat plate with zero pressure gradient. Based on this test problem, it was found that the low Reynolds number k-ε model of Chen and Patel

gives excellent results. But, the RNG k-ε model yielded unsatisfactory results. A paper describing the details of RAAKE (formulation, algorithm, and code) as well as the results of the aforementioned tests will be written [Ref. 7].

4. Efforts were made to understand errors created by using chimera grids because the use of such grids can facilitate greatly the simulation of three-dimensional (3-D) bleed-hole problems involving circular holes. Based on this study, a suitable chimera grid for 3-D, shock-wave/boundary-layer interactions on a flat plate with a single circular bleed hole was identified.

2.2 Second Year

During the second grant year beginning on January 1, 1992 and ending on December 31, 1992, the following accomplishments were made:

1. Completed a 3-D study of shock-wave/boundary-layer interactions on a flat plate with bleed through a single circular hole that vent to a plenum. This work is unique for the following reasons:
   a. A solution-adaptive grid was used to resolve the incident and reflected shock wave. This grid allowed the shock waves to be captured very sharply.
   b. The overall grid employed was a Chimera grid.
   c. Discovered the formation of a bow shock, referred to as a "barrier" shock, within the bleed hole and explained why and how it forms and how it can be used to prevent upstream influence length.
   d. Explained how bleed hole placement affect upstream, downstream, and spanwise influence lengths.

   References 8 and 9 describe this work.
2. The robustness of RAAKE code was further improved by enhancing the numerical method of solution. In particular, the following were added into RAAKE: (a) an option

involving Newton-Raphson iteration in which the system of linearized equations are solved by alternating-direction Gauss-Seidel iteration with successive-overrelaxation and (b) several different ways of treating source terms to ensure monotonicity of the solutions. The new features added were found to be essential when simulating turbulent flows with shock waves.

3. The k-ε model of Jones and Launders was added into RAAKE. This turbulence model accounts for the physics in both low and high Reynolds number regions. When computing low Reynolds number turbulent flows, it does not require knowledge about the distance from the wall.
4. RAAKE was used to obtain a preliminary solution of supersonic, turbulent boundary-layer flow past a compression corner in which separation takes place.

The work described under items 2 to 4 above will also be reported in Ref. 7.

2.3 Third Year

During the third grant year beginning on January 1, 1993 and ending on December 31, 1993, the following accomplishments were made:

1. Completed a study of 3-D shock-wave/boundary-layer interaction on a flat plate with bleed as a function of pressure ratio, number of bleed holes, and angle of bleed holes. Reference 10 describes this work.
2. Completed a study of 3-D shock-wave/boundary-layer interaction on a flat plate with bleed through four rows of staggered holes. Reference 11 describes this work.
3. Vectorized RAAKE. For the compression corner problem with 175x3x175, OVERFLOW with Baldwin & Lomax requires 4.95 seconds/step whereas OVERFLOW with RAAKE (k-ε or k-ω) requires 5.66 seconds/step.

4. Fully incorporated RAAKE into OVERFLOW allowing for overlapping grids with general boundary conditions for turbulence including IBLANK. The only boundary condition not supported at this time is periodic and wrap-around boundary conditions.
5. Added k-ω model into RAAKE. Thus, there are now two low-Reynolds-number two-equation models of turbulence in RAAKE that do not require knowledge about the normal distance from solid walls.
6. Developed and implemented new "initial condition" routines for k-ε and k-ω models for internal and external flows.
7. Added second-order spatial differencing to turbulence models in RAAKE.
8. Obtained some preliminary results for subsonic flow past a row of vortex generators (see Ref. 12).

The work described under items 3 to 7 above will be reported in Ref. 7.

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